AFRL-RV-PS-
TR-2015-0083

AFRL-RV-PS-
TR-2015-0083

INTEGRATED GRAPHENE-BASED OPTOELECTRONIC DEVICES USED FOR ULTRAFAST OPTICAL-THZ PHOTODETECTORS, MODULATORS AND EMITTERS

Godfrey Gumbs

Research Foundation of the City University of New York
230 W 41st Street FL7
New York, NY 10036

3 Apr 2015

Final Report

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED.

AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

DTIC COPY
NOTICE AND SIGNATURE PAGE

AFRL-RV-PS-TR-2015-0083 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//SIGNED//
DANHONG HUANG
Program Manager

//SIGNED//
PAUL D. LEVAN, Ph.D.
Technical Advisor, Space Based Advanced Sensing and Protection

//SIGNED//
JOHN BEAUCHEMIN
Chief Engineer, Spacecraft Technology Division
Space Vehicles Directorate

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
03-04-2015

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
7 Nov 2011 – 12 Feb 2012

4. TITLE AND SUBTITLE
Integrated Graphene-Based Optoelectronic Devices Used for Ultrafast Optical-THz Photodetectors, Modulators and Emitters

5a. CONTRACT NUMBER
FA9453-12-1-0135

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
63401F

6. AUTHOR(S)
Godfrey Gumbs

5d. PROJECT NUMBER
2181

5e. TASK NUMBER
PPM00019528

5f. WORK UNIT NUMBER
EF124506

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Foundation of the City University of New York
230 W 41st Street FL7
New York, NY 10036

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Space Vehicles Directorate
3550 Aberdeen Ave., SE
Kirtland AFB, NM 87117-5776

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVSS

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RV-PS-TR-2015-0083

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The purpose is to investigate the research on fundamentals of quasiparticles in graphene electrons, phlasmons and electron-hole pairs with the ultimate goal to convert them into or be extracted from terahertz electromagnetic radiation.

15. SUBJECT TERMS
graphene, transport, imperfections or disorder, or impurities, conductance

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	Unlimited	14	Danhong Huang
					19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

(This page intentionally left blank)

Table of Contents

(This page intentionally left blank)

1 Summary

We carried out numerical simulations on multilayer plasmon excitations by resonant energy transfer. A formal derivation of the transfer rate from the plasmons to the Wannier excitons was performed. We stimulated fluorescence and compared our results with the conventional organic/inorganic hybrid organic light-emitting diode (OLEDs).

2 Introduction

We formulated electron energy loss spectroscopy (EELS) for multilayer epitaxial grapheme.

Our derivation of the general angles-resolved EELS spectra for transmission and reflection is based on the prescribed electron trajectory. In particular, we were interested in application of the theory to various multi-layer electron gas (MLEG) configurations, i.e., epitaxial vs. exfoliated graphene.

We did a comparison with the available experimental data to see the effect of the gap between the valence and conduction bands.

3 Methods, Assumptions, and Procedures

We initiated a study of the plasma instability in graphene double-layers in interaction with a thick conductor when an electric current is passed through one of the layers.

For optoelectronic detectors, we investigated the relation between the induced and driving currents via nonlocal response.

Comparison of the plasmon generation with conventional two-dimensional electron gas (2DEG) configurations was initiated. The role of the gap and interband polarization was investigated. The aim was converting plasmonic energy to THz radiation using a grating.

We carried out a study of dressed Dirac electrons trapped in a quantum dot by coherent nonlinear THz spectroscopy.

In our published paper “Tunable electromagnetic coupling among two-dimensional electron gas, graphene micro-ribbon and surface plasmons”, a self-consistent theory involving Maxwell equations and a density-matrix linear-response theory is solved. The conditions of the solution include an electromagnetically-coupled doped graphene micro-ribbon array and a quantum-well electron gas sitting at an interface between a half-space of air and another half-space of a doped semiconductor substrate which supports a surface-plasmon mode in our system. The coupling between a spatially-modulated total electromagnetic field and the electron dynamics in a Dirac-cone of a graphene ribbon, as well as the coupling of the far-field specular and near-field higher-order diffraction modes, is included in the derived electron optical-response function. Full analytical expressions are obtained with non-locality for the optical-response functions of a two-dimensional electron gas and a graphene layer with an induced bandgap, and are employed in our

numerical calculations beyond the long-wavelength limit. Both the transmissivity and reflectivity spectra, as well as their dependence on different configurations of our system and on the array period, ribbon width, graphene chemical potential, drift velocity of quantum-well electron gas and bandgap in graphene, are studied. Moreover, the transmitted E-field intensity distribution is calculated to demonstrate its connection to the mixing of specular and diffraction modes of the total electromagnetic field. An externally-tunable electromagnetic coupling among the surface, conventional electron-gas and massless graphene intraband plasmon excitations is discovered and explained. Furthermore, a comparison is made between the dependence of the graphene-plasmon energy on the ribbon width and chemical potential in this paper and the recent experimental observation given by Ju, et al., [Nature Nanotechnology **6**, 630 (2011)] for a graphene micro-ribbon array in the terahertz-frequency range.

We investigated the energy transfer properties of a novel nanocomposite consisting of a quantum dot and graphene nanoparticle. The nanocomposite is embedded in a photonic crystal. Energy transfer occurs when electronic excitons in the quantum dot and surface plasmons in graphene interact through the dipole-dipole interaction. Two dressed correlated excitons are created in the quantum dot, corresponding to two peaks in the loss function. It was shown that the exciton energies may be transferred to graphene through the dipole-dipole interaction. Additionally, this energy transfer may be switched on and off by applying a pump laser to the photonic crystal or by adjusting the strength of the dipole-dipole interaction. The intensity of the peaks for the loss function increases when the number of graphene layers is increased or the separation between the quantum dot and graphene is decreased. The principle of our nanocomposite may be employed to fabricate nano-biosensors, optical nano-switches, energy transfer devices and quantum tele-transportation devices.

4 Results and Discussion

The properties of the high energy optical π-plasmons of simple hexagonal intrinsic graphite were calculated within the self-consistent-field approximation. The plasmon frequency ω_p was determined as functions of the wave vector $\boldsymbol{q}_{||}$ along the hexagonal plane in the Brillouin zone and the perpendicular component q_z. When $q_z = 0$, the plasmons exist for wave vectors larger than a critical wave vector $q_c \sim 0.02\ A^{-1}$. These plasmons are isotropic within the plane in the long wavelength limit and for $q_{||} > q_c$. As the wave vector $q_{||}$ increases, the plasmon frequency strongly depends on the magnitude and direction (ϕ) of $\boldsymbol{q}_{||}$. With increasing ϕ, the dispersion relation of ω_p-$(q_{||})$ is gradually changed from quadratic to nearly linear form. There are many significant differences for the π-plasmon dispersion relations between 2D graphene and 3D *AA*-stacked graphite. They include threshold frequency, critical transferred momentum, $q_{||}$- and ϕ-dependence and π-plasmon bandwidth. This result reveals that interlayer interactions could enhance anisotropy of in-plane π-plasmons. For chosen $q_{||} > q_c$, we also obtain the ω_p as a function of q_z and show that there is an upper bound on q_z for plasmons to exist in graphite.
We presented the formalism and numerical results for the energy loss of a charged particle scattered at an arbitrary angle from epitaxially-grown multilayer graphene (MLG). It was compared with that of free-standing graphene layers. Specifically, we investigated the effect of the substrate-induced energy gap on one of the layers. The gap yields collective plasma oscillations whose characteristics were qualitatively and quantitatively different from those

produced by Dirac fermions in gapless graphene. The range of wave numbers for undamped self-sustaining plasmons was increased as the gap was increased, thereby increasing and red-shifting the MLG stopping power for some range of charged particle velocity. We also applied our formalism to interpret several distinct features of experimentally-obtained electron energy loss spectroscopy (EELS) data.

5 Conclusions

We calculated the edge-plasmon excitation spectrum within the anti-crossing bulk bandgap region for an inverted HgTe/CdTe quantum well by employing the Bernevig, Hugues and Zhang (BHZ) model within the random-phase approximation (RPA). Our proposed model system consists of a single component electron helical liquid (HL) in a semi-infinite quantum well, in which a topological state that is localized around the system edge can exist. With linearly-polarized incident light as a perturbation to such a single component HL, the unique charge dynamics for collective excitation of these edge-bound electrons with broken time-reversal symmetry was investigated. The plasmon dispersion $\omega_p(q)$ of the single component HL has the form $\omega_p(q) \sim -\omega_0 q \ ln(qa)$ in the long-wavelength limit, which is in sharp contrast with $\omega_p(q) \sim -\omega_0 q \ [-ln(qa)]^{1/2}$ for a one-dimensional electron gas (1DEG) in a quantum-wire system. Here, the plasmon wave number in a conventional 1DEG is scaled with a characteristic width *W*, while that in our model system is scaled with a lattice constant *a*. Similar to interband plasmons in a metallic armchair graphene nanoribbon, ω_0 was found to be independent of the linear electron density for the intraband plasmon in our system. Besides the spin factor of two and *W* scaling for the wave number, the dispersion relation for the collective excitation of the two-component HL is the same as that in an armchair graphene nanoribbon. The particle-hole excitation region in our system is found to be collapsed into a straight line, instead of a wide region for a conventional 1DEG. The plasmon energies of the two and single-component HL are spectrally separated although the same particle-hole excitation region is shared by both of them.

A dilute distribution of magnetic impurities was assumed to be present in doped graphene. We calculated the interaction energy between two magnetic impurities which are coupled via the indirect-exchange or Ruderman-Kittel-Kasuva-Yosida (RKKY) interaction by the doped conduction electrons. Our model was a half-filled AB-lattice structure. The calculations were based on the retarded lattice Green's function formalism in momentum-energy space which was employed in linear response theory to determine the magnetic susceptibility in coordinate space. Analytic results are obtained for gapped graphene when the magnetic impurities were placed on the *A* and *B* sublattice sites of the structure. This interaction, which is important in determining spin ordering, has been found to be significantly different for *AA* and *BB* exchange energies in doped graphene due to the existence of an energy gap, and is attributed to a consequence of the local fields not being equal on the *A* and *B* sublattices. For doped graphene, the oscillations of all three RKKY interactions from ferromagnetic to antiferromagnetic with increasing Fermi energy is significantly modified by the energy gap both in magnitude and phase. Additionally, the *AB* exchange energy may be modified by the presence of a gap for undoped graphene but not for doped graphene due to the dominance of doped conduction electrons.

APPENDIX: SUMMARY OF MAJOR ACCOMPLISHMENTS

Below, I give a brief summary of the major accomplishments. This is a list of related works which were also carried out under this contract:

1. S. J. Wright, A. L. Thorn, M. D. Blumenthal, S. P. Giblin, M. Pepper, T. J. B. M. Janssen, M. Kataoka, J. D. Fletcher, G. A. C. Jones, C. A. Nicoll, Godfrey Gumbs, and D. A. Ritchie, "Single- and few-electron dynamic quantum dots in a perpendicular magnetic field," Journal of Applied Physics, **109**, 102422 (2011).

2. Danhong Huang, Godfrey Gumbs, and O. Roslyak, "Field-enhanced electron mobility by nonlinear phonon scattering of Dirac electrons in semiconducting graphene nanoribbons," Physical Review B, **83**, 115405 (2011).

3. Jhao-Ying Wu, Szu-Chao Chen, O. Roslyak, Godfrey Gumbs, and Ming-Fa Lin, "Plasma excitations in graphene: their spectral intensity and temperature dependence in magnetic field," ACS Nano, **5**, 1026-1032 (2011).

4. Oleksiy Roslyak, Godfrey Gumbs, and Danhong Huang, "Plasma excitations of dressed Dirac electrons in graphene," Journal of Applied Physics, **109**, 113721 (2011).

5. Godfrey Gumbs, O. Roslyak, Danhong Huang, and Antonios Balassis, "Spectroscopic characterization of gapped graphene in the presence of circularly polarized light," Journal of Modern Optics, **58**, 1990-1996 (2011).

6. Danhong Huang, Godfrey Gumbs, and O. Roslyak, "Optical modulation effects on nonlinear electron transport in graphene in terahertz frequency range," Journal of Modern Optics, **58**, 1898-1907 (2011).

7. Godfrey Gumbs, Antonios Balassis, Danhong Huang, Sheehan Ahmed, and Ryan Brennan, "A half-step in quantized conductance for low-density electrons in a quantum wire," Journal of Applied Physics, **110**, 073709 (2011).

8. Andrii Iurov, Godfrey Gumbs, Oleksiy Roslyak, and Danhong Huang, "Anomalous photon-assisted tunneling in graphene," Journal of Physics: Condensed Matter, **24**, 015303 (2012).

9. Oleksiy Roslyak, Godfrey Gumbs, and S. Mukamel, "Trapping photon-dressed Dirac electrons in a quantum dot studied by coherent two dimensional photon echo spectroscopy," Journal of Chemical Physics, **136**, 194106 (2012).

10. O. Roslyak, Godfrey Gumbs, and Danhong Huang, "Energy loss spectroscopy of epitaxial versus free-standing multilayer graphene," Physica E: Condensed Matter, **44**, 1874-1884 (2012).

11. C. W. Chiu, F. L. Shyu, M. F. Lin, Godfrey Gumbs, and Oleksiy Roslyak, "Anisotropy of π-plasmon dispersion relation of AA-stacked graphite," Journal of the Physical Society of Japan, **81**, 104703 (2012).

12. Joel D. Cox, Mahi R. Singh, Godfrey Gumbs, M. A. Anton, and F. Carreno, "Energy exchange rate between a quantum dot and a graphene sheet embedded in a photonic crystal," Physical Review B, **86**, 125452 (2012).

13. Oleksiy Roslyak, Godfrey Gumbs, and S. Mukamel, "Nonlinear spectroscopy of photon-dressed Dirac electrons in a quantum dot," Journal of Modern Optics, **60**, 58-64 (2012).

List of Acronyms

1DEG	one-dimensional electron gas
2DEG	two-dimensional electron gas
BHZ	Bernevig, Hugues and Zhang
EELS	Electron energy loss spectroscopy
HL	Helical Liquid
MLEG	Multi-layer electron gas
MLG	multilayer graphene
OLEDs	hybrid organic light-emitting diode
RPA	Random-phase approzimation
RKKY	Ruderman-Kittel-Kasuva-Yosida

DISTRIBUTION LIST

DTIC/OCP 8725 John J. Kingman Rd, Suite 0944 Ft Belvoir, VA 22060-6218	1 cy
AFRL/RVIL Kirtland AFB, NM 87117-5776	2 cys
Official Record Copy AFRL/RVSS/Danhong Huang	1 cy

(This page intentionally left blank)